Lower-Limb Kinematics of Single-Leg Squat Performance in Young Adults

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ABSTRACT

Purpose: To determine the kinematic parameters that characterize good and poor single-leg squat (SLS) performance. **Methods:** A total of 22 healthy young adults free from musculoskeletal impairment were recruited for testing. For each SLS, both two-dimensional video and three-dimensional motion analysis data were collected. Pelvis, hip, and knee angles were calculated using a reliable and validated lower-limb (LL) biomechanical model. Two-dimensional video clips of SLSs were blindly assessed in random order by eight musculoskeletal physiotherapists using a 10-point ordinal scale. To facilitate between-group comparisons, SLS performances were stratified by tertiles corresponding to poor, intermediate, and good SLS performance. **Results:** Mean ratings of SLS performance assessed by physiotherapists were 8.3 (SD 0.5), 6.8 (SD 0.7), and 4.0 (SD 0.8) for good, intermediate, and poor squats, respectively. Three-dimensional analysis revealed that people whose SLS performance was assessed as poor exhibited increased hip adduction, reduced knee flexion, and increased medio-lateral displacement of the knee joint centre compared to those whose SLS performance was assessed as good ($p \leq 0.05$). **Conclusions:** Overall, poor SLS performance is characterized by inadequate knee flexion and excessive frontal plane motion of the knee and hip. Future investigations of SLS performance should consider standardizing knee flexion angle to illuminate other influential kinematic parameters.

Key Words: kinematics; knee joint; leg injuries; musculoskeletal physiological phenomena.

RÉSUMÉ

Objectif : Déterminer les paramètres cinématiques qui caractérisent un bon et un mauvais rendement de la flexion de la jambe. **Méthodes :** On a recruté au total 22 jeunes adultes en santé qui n'avaient aucun déficit de l'appareil locomoteur. Pour chaque flexion de la jambe, on a réuni des données d'analyses vidéos bidimensionnelles et d'analyses du mouvement tridimensionnelles. Les angles du bassin, de la hanche et du genou ont été calculés au moyen d'un modèle biomécanique fiable et validé des membres inférieurs. Des capsules vidéos bidimensionnelles des flexions de la jambe ont été évaluées à l'insu et au hasard par huit physiothérapeutes spécialistes de l'appareil locomoteur qui ont utilisé une échelle ordinale à 10 points. Afin de faciliter les comparaisons entre groupes, on a stratifié le rendement de la flexion de la jambe par tertiles correspondant à un rendement médiocre, moyen et bon. **Résultats :** Les cotes moyennes du rendement de la flexion de la jambe évalué par les physiothérapeutes se sont établies à 8,3 (ET 0,5), 6,8 (ET 0,7) et 4,0 (ET 0,8) pour un rendement bon, moyen et médiocre respectivement. L'analyse tridimensionnelle a révélé que les gens dont le rendement de la flexion de la jambe était médiocre montraient une adduction accrue de la hanche, une réduction de la flexion du genou et un déplacement médio-latéral accru du centre de l'articulation du genou comparativement à ceux dont le rendement a été jugé bon ($p \leq 0,05$). **Conclusions :** Dans l'ensemble, un rendement médiocre de la flexion de la jambe est caractérisé par une flexion inadéquate du genou et un mouvement excessif du plan frontal du genou et de la hanche. Les études futures portant sur le rendement de la flexion de la jambe devraient envisager de normaliser l'angle de flexion du genou afin d'éclairer d'autres paramètres cinématiques influents.

The single-leg squat (SLS) test is commonly used by clinicians to assess pelvic and lower-limb (LL) joint stability.^{1–3} In clinical practice, the quality of SLS performance is often rated visually on a 10-point ordinal scale, with poor scores (typically <5) indicating a propensity for common degenerative and traumatic musculoskeletal injuries.^{4–6} Despite its widespread clinical use, however,

the SLS test has been found to have only modest inter- and intra-tester reliability,^{4,7,8} and its sensitivity to joint-specific kinematic abnormalities is questionable.⁷ A thorough three-dimensional (3D) investigation of SLS kinematics is therefore required to reveal the joint-specific movement patterns that clinically differentiate a good performance from a poor performance.

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Biomechanical investigations of the SLS have focused on narrow demographic cohorts^{1,3,9} or have included people with known musculoskeletal conditions such as patellofemoral pain syndrome or anterior cruciate ligament (ACL) injury.^{2,6,10} Curiously, no study has reported the 3D LL kinematic parameters that differentiate good from poor SLS performance. Our aim in this study, therefore, was to examine the 3D LL joint and segment kinematics that typify good and poor SLS performances in healthy young adults (as a result, intermediate performances are not a focus of this brief report). We hypothesized that a poor SLS would be characterized by greater pelvic obliquity, hip adduction, and knee medio-lateral displacement than a good SLS.

METHODS

The Griffith University Human Research Ethics Committee granted approval for the study (PES/27/11/HREC); we obtained written informed consent from each participant, and all research activities were conducted in accordance with the Declaration of Helsinki.

Participants

We used a quasi-experimental design to examine SLS performance in 22 healthy young adults (13 male, 9 female; mean age 23.8 [SD 3.1] years; mean height 1.73 [SD 0.07] m; mean mass 69.4 [SD 12.7] kg). All participants were free from musculoskeletal impairment or injury at the time of testing.

Video collection and rating

Each participant performed three SLSs on each leg while video data were collected with a high-definition digital video camera (Sony DCR-SX40E, Sydney, Australia). The camera was positioned in front of each participant at a distance of 3 m and a height of 1 m. To minimize the influence of clothing on SLS ratings, men were required to wear sports shorts while women wore shorts and a close-fitting athletic singlet. For each SLS, participants were instructed to stand on one leg with arms folded across their chest, looking straight ahead, before flexing at the hip and knee in a slow, controlled manner without losing balance. Each participant was permitted three practice attempts before data collection. Commensurate with previous investigations,^{1,11–13} and to most closely resemble clinical practice, squat depth was not standardized.

Following laboratory data collection, two-dimensional video clips of each SLS were assessed confidentially and privately by eight postgraduate-qualified musculoskeletal physiotherapists using a 10-point ordinal scale (1 = lowest, 10 = highest). Clips were viewed on a desktop computer with a 22" widescreen LCD monitor. Ratings were used to derive a mean performance score for each SLS. An equivalent approach was adopted by Crossley and colleagues,¹¹ who reported excellent inter-rater agreement (80–87% $\kappa = 0.700$ – 0.800) for similarly qualified physiotherapists.

Figure 1 Individual and cluster-based markers used in three-dimensional kinematic analysis.

Three-dimensional data collection

We collected 3D kinematic data simultaneously with video data using a 10-camera Vicon motion analysis system (MX13 Cameras, Oxford Metrics, Oxford, UK) operating at 200 Hz. Retro-reflective markers were attached to specific anatomic landmarks including the second metatarsal head, medial and lateral malleoli, calcaneus, medial and lateral femoral condyles, and right and left anterior superior and posterior superior iliac spines; in addition, clusters of four markers were attached to the shank and thigh segments (see Figure 1). Following marker placement, we performed a series of calibration trials to define anatomic landmarks within each segment's technical coordinate system and to establish neutral joint positions. Hip and knee joint centres were calculated from functional movement tasks,^{14,15} which allowed us to determine joint centres independently of marker placement and thus improved the reliability of the kinematics. We identified hip joint centres by fitting a sphere to the motion of thigh markers, while knee joint flexion-extension axes were identified using the mean helical axis method described by Besier and colleagues.^{14,16}

Raw 3D coordinate data were filtered using a zero-lag fourth-order low-pass Butterworth filter with a cut-off frequency of 8 Hz as determined through residual analysis.¹⁷ We used the filtered marker trajectories to compute 3D segment and joint angles using the Euler angle method in conjunction with BodyBuilder software, version 3.6 (Vicon, OxfordMetrics). The convention used to describe LL segment and joint kinematics was in accordance with the recommendations of the International Society of Biomechanics^{18–20} and followed a flexion-extension, abduction-adduction, and internal-external rotation sequence. For the pelvis specifically, *tilt* represented rotation around the medio-lateral axis, *obliquity* represented rotation around the anterior-posterior axis, and *axial rotation* represented rotation around the vertical axis. Knee medio-lateral displacement represented

Figure 2 Ensemble averages for selected three-dimensional lower-limb kinematic parameters for good and poor SLS performances. Error bars (single-sided) represent 95% CIs.

^ Data presented in mm.

displacement (in mm) of the knee joint centre in the medio-lateral (x-y) plane.

Statistical analyses

We stratified mean physiotherapist ratings of SLS performance by tertile to facilitate comparison of good and poor SLSs. For between-group comparisons of kinematic parameters (peak pelvis, hip, and knee 3D angles), we used one-way analyses of variance (ANOVA); assumptions of normality were checked and confirmed by plotting dependent variables using quantile-quantile plots. All statistical analyses were performed using SPSS for Windows, version 19.0 (IBM, Chicago, IL). The threshold for statistical significance was set at $p < 0.05$, and effect sizes (ES) are reported as Cohen's d .²¹

RESULTS

SLS performance

Mean rating of SLS performance as assessed by the musculoskeletal physiotherapists was 6.3 (SD 1.9, range 2.4–9.1); the upper (i.e., good), middle, and bottom (i.e., poor) tertiles yielded mean ratings of 8.3 (SD 0.5), 6.8 (SD 0.6), and 4.0 (SD 0.8), respectively.

Three-dimensional SLS kinematics

Figure 2 shows ensemble average angular displacement profiles (with 95% CIs) for poor and good SLSs. Overall, 3D pelvis profiles were similar between groups except for pelvis anterior tilt, which, although similar in amplitude, occurred earlier during a good SLS. For hip

Table 1 Lower-Limb Kinematics for Good and Poor Single-Leg Squats in Young Healthy Adults

Kinematic variable	Mean (SD)		<i>p</i> -value	ES (Cohen's <i>d</i>)
	Good SLSs	Poor SLSs		
Pelvis tilt, °	−14.1 (2.7)	−13.2 (3.1)	ns	−0.32
Pelvis obliquity, °	5.7 (5.1)	8.5 (4.5)	ns	−0.60
Pelvis rotation, °	−3.4 (3.6)	−5.2 (5.0)	ns	0.43
Hip flexion, °	88.0 (8.6)	80.3 (9.8)	ns	0.87
Hip adduction, °	14.7 (4.7)	22.4 (6.1)	<i>p</i> < 0.01	−1.47
Hip rotation, °	−15.6 (5.0)	−15.2 (5.2)	ns	−0.08
Knee flexion, °	90.1 (12.1)	73.1 (8.7)	<i>p</i> < 0.01	1.67
Knee m-l displacement, mm	38.4 (14.3)	53.7 (16.8)	<i>p</i> = 0.02	−1.02
Ankle flexion, °	35.3 (11.2)	29.9 (7.6)	ns	0.59

SLSs = single-leg squats; ES = effect size; ns = not significant ($p \geq 0.05$); m-l = medio-lateral.

and knee joint motion, we observed clear differences in the magnitude of angular displacement profiles.

Characteristics of good and poor SLS performance

ANOVA results revealed that poor SLSs were characterized by greater hip adduction (22.4° [SD 6.1°] vs. 14.7° [SD 4.7°]; $p < 0.01$, ES = −1.47), lesser knee flexion (73.1° [SD 8.7°] vs. 90.1° [SD 12.1°]; $p < 0.01$, ES = 1.67), and greater medio-lateral displacement of the knee joint centre (53.7 [SD 16.8] mm vs. 38.4 [SD 14.3] mm; $p = 0.02$, ES = −1.02) than good SLSs (see Table 1).

DISCUSSION

The purpose of our study was to determine the LL kinematic parameters that characterize good and poor SLS performance in healthy young adults. Using a reliable and validated LL biomechanical model,¹⁴ we observed greater hip adduction and knee medio-lateral displacement and lesser knee flexion in SLSs classified as poor than in those classified as good.

In agreement with our hypotheses, poor SLSs were characterized by excessive peak hip joint adduction and knee medio-lateral displacement relative to good SLSs. Interestingly, similarly undesirable LL kinematics have been observed in clinical patient populations, including those with patello-femoral pain syndrome^{6,10,22} and those with a history of ACL injury.² Furthermore, Hewett and colleagues⁵ prospectively followed a large cohort of female athletes and found that those who demonstrated large knee abduction angles or dynamic valgus during baseline landing tasks were most likely to experience an ACL injury in the future. The fact that hip adduction and knee medio-lateral displacement was greater in poor SLSs than in good SLSs suggests that hip abductor weakness may be responsible for the sub-optimal performance.^{1,23,24} Other possible reasons for poor performance include muscular or joint-related movement restrictions, anatomic and biomechanical factors such as an increased Q-angle, and the adoption of a preferred

pattern of movement. The position of the trunk, however, should not be discounted as a contributor to increased knee medio-lateral displacement, as the large relative mass of the trunk has the potential to influence the position of the body's centre of mass in the frontal plane and thus to affect hip and knee loading during activities such as the SLS.²⁴

The finding of greater peak knee flexion angles in good SLS performances than in poor SLS performances, on the other hand, does not support our initial hypothesis that differences would be observed only in the frontal plane. Although the presence of LL joint pain and/or muscle inhibition (e.g., quadriceps) may help explain reduced knee flexion during the SLS in a clinical population,²⁵ the fact that we observed less knee flexion in our pain-free participant sample suggests other underlying factors. Quadricep weakness, limited ankle dorsiflexion range, poor motivation, and misinterpretation of test instructions are all plausible explanations for reduced knee flexion.^{24,26} While it is difficult to control such varied intrinsic and extrinsic factors, we propose that if researchers are to continue to use the SLS as a clinical assessment tool, a standardized knee flexion angle should be considered.

Our study has several limitations. First, SLS performance was determined by averaging ratings from a group of experienced physiotherapists who generated scores from video data; the authenticity of such observations may not adequately reflect clinical practice, which may have influenced their ratings. Second, the presence of reflective markers attached to participants' limbs during video observation—essential for measuring 3D kinematics—may also have influenced therapists' ratings.

Future investigation of LL muscle contributions to SLS performance using muscle-driven forward dynamic models will help establish muscle-specific recommendations for exercise intervention.

CONCLUSIONS

Compared to a good SLS, poor SLS performance in people free from musculoskeletal injury was characterized by lesser knee flexion and greater hip adduction and knee medio-lateral displacement. Researchers should consider standardizing knee flexion angle when investigating the biomechanics of the SLS. Moreover, clinicians must appreciate the extent to which knee flexion determines performance and ensure a consistent approach when comparing symptomatic and non-symptomatic limbs or when screening for injury risk.

KEY MESSAGES

What is already known on this topic

Published data for the single-leg squat (SLS) test has typically involved reporting kinematics and/or muscle activity in various patient populations (e.g., knee pain vs. no knee pain). Such investigations have not been based on gold standard motion analysis techniques; many studies have reported data derived from 2D projections of 3D angles. To date, no study has reported the 3D lower-limb kinematic parameters that differentiate good SLS performance from poor SLS performance.

What this study adds

In young adults free from musculoskeletal injury, poor SLS performance is characterized by lesser knee flexion and greater hip adduction and knee medio-lateral displacement. Given the kinematic differences between good and poor SLS performances, researchers should consider standardizing knee flexion angle when using the SLS as an outcome measure. Clinicians must also appreciate the extent to which knee flexion determines SLS performance and ensure a consistent approach when comparing symptomatic and non-symptomatic limbs.

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